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Asphalt Mix Compressive Stress-Strain Behavior: An Analytical and Experimental Study of Variable Influence

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Abstract

To address the excessive depletion of natural resources in Indonesia's civil construction sector, there's a rising trend in utilizing plastic waste from packaging, such as beverage bottles and plastic bags, alongside renewable energy sources like Modified Buton Asphalt (MBA). MBA serves as a partial substitute for both fine and coarse natural aggregates and non-renewable energy sources like petroleum bitumen. This study aimed to investigate the effects of incorporating polyethylene terephthalate (PET) and polypropylene (PP) waste as partial substitutes for coarse and fine aggregates through experiments and t-tests. The objective was to determine how the stress-strain behavior of asphalt mixtures formed using MBA changed with the addition of this mixture. Additionally, compressive strength and elastic modulus were calculated under mixed compressive loads. PET and PP plastic waste replaced natural coarse and fine aggregates at three volume percentages: 1%, 2%, and 3%, with a PET:PP ratio of 50%. A manual grater was used to shred PET and PP plastic bottles into shredded plastic waste, which was retained in sieve no. 50 after sieving. The study found that adding PET, PP plastic, and MBA waste enhanced the asphalt mixture's mechanical strength and modified relevant variables, resulting in a more elastic and ductile behavior.

Keywords: Asphalt Mix, Compressive Stress-Strain, PET, PP, MBA.

1. Introduction

In Indonesia, asphalt concrete (AC), also referred to as the asphalt concrete layer, is a commonly used type of flexible pavement. Typically, three layers of asphalt concrete are utilized: the asphalt concrete wearing course (AC-WC), asphalt concrete binder course (AC-BC), and asphalt concrete base (AC-base) [1–4]. The binder layer of the AC-BC asphalt mixture typically exhibits a gradation that is coarser than AC-WC but finer than AC-base. Asphalt concrete layers are frequently employed in regions experiencing high deformation, such as those near traffic lights, toll gates, mountainous terrain, or areas with high traffic volume.

The stability of an asphalt road pavement layer, defined as its ability to endure traffic loads without permanent deformation, is essential. However, in practice, road pavements often suffer damage over time or fail to meet their expected service life. Figure 1 illustrates the aging process of bitumen, from mixing to storage, application, transportation, and in-service use. The presence of voids in the mixture plays a crucial role in bitumen hardening, particularly in surface courses. Bitumen extracted from mixtures with minimal void content exhibited minimal hardening. Conversely, significant hardening occurred in mixtures with high void content, facilitating continuous air ingress [5–7].

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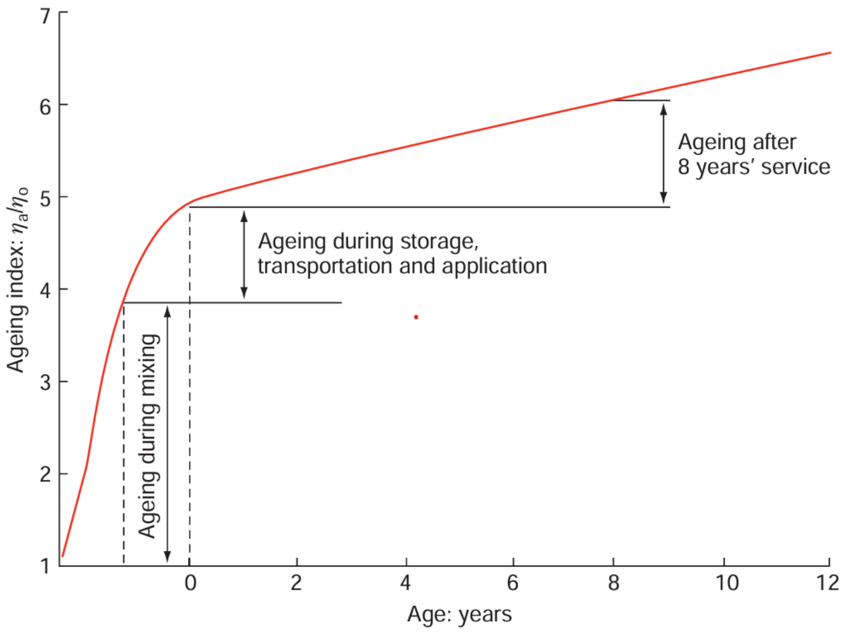


Figure 1. Bitumen aging after mixing, then during storage, application, transportation, then in service [5]

For various purposes, such as performance evaluation, mix or pavement design, and adherence to production or construction specifications, understanding the properties of asphalt mixes is essential. Engineers typically rely on laboratory tests to determine, characterize, or predict the material properties of asphalt mixtures, as conducting in-situ testing of material properties in the field, either through full-scale tests or on compacted pavement, is often challenging for road construction planners and implementers, or it may not be economically feasible. Testing may also be necessary to ensure that the requirements are met. To examine specific aspects of in-situ behavior, several tests have been developed and categorized into three groups. The first group comprises fundamental tests such as indirect tensile tests, dynamic stiffness and fatigue tests, repeated load testing, static creep tests, and static stiffness tests. The second group includes simulation testing in the laboratory, such as wheel tracking tests, gyratory compaction, durability, and cracking tests. The third group consists of empirical tests, including the Marshall test and the indirect tensile strength test [5]. Figure 2 illustrates the strains exerted on a typical pavement element by an approaching tire load.

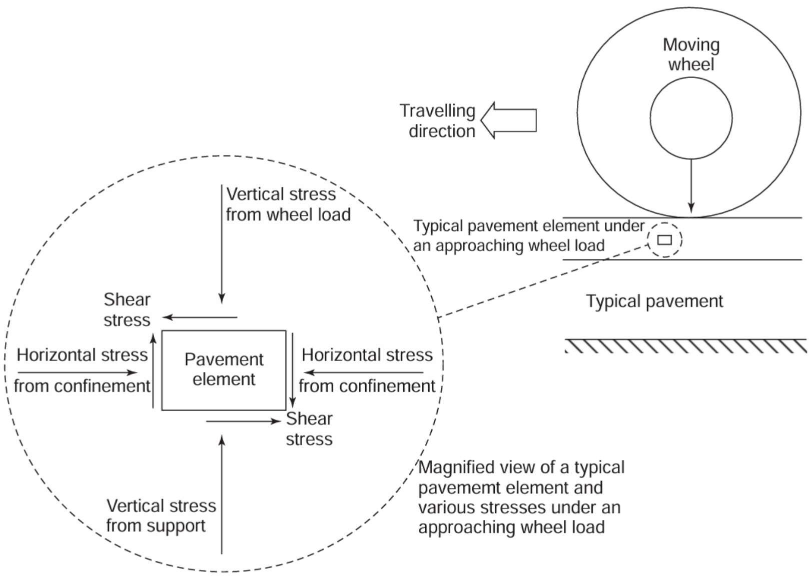


Figure 2. The strains placed on a typical pavement element by an approaching tire load [5]

In Indonesia, there have been numerous instances where the service life of roads was reduced by 25.94%, equivalent to 4.3 years, or even by 1.5 to 2 years from the intended 10-year lifespan. According to statistics from the Department of Public Works and Public Housing [8–10], only 62% of Indonesia's roads are in good condition, with the remaining roads either lightly damaged or severely deteriorated. The increasing traffic density is a major contributing factor to road damage and reduced longevity. Angelone et al. (2016) [11] suggested that repetitive traffic loads associated with high traffic density result in the accumulation of permanent deformation in asphalt concrete mixtures, thereby compromising road performance. One solution to address this issue is the incorporation of chemicals into the mixture.

Currently, both domestically and internationally, the incorporation of additional components in asphalt concrete mixtures is widespread, particularly the utilization of residual or waste materials, which pose significant environmental challenges, including plastic waste. Plastics, in particular, require hundreds or even thousands of years to decompose and return to the soil, contributing to a global crisis of plastic pollution. This issue is prevalent not only in underdeveloped nations but also in industrialized countries like the United States, England, and Japan. In Western European countries, the per capita consumption of plastic materials reaches 60 kg/year, while in the United States, it reaches 80 kg/year, and in the United Kingdom, it results in at least 3 million tons of plastic waste annually, according to the Indonesia Solid Waste Association (2013) [11, 12]. Plastic debris constitutes approximately 57 percent of the waste found on beaches, and every square mile of water contains as much as 46,000 pieces of floating plastic waste. The depth of plastic debris in the Pacific Ocean has even reached nearly 100 meters.

The Asbuton deposit, located on Buton Island in Southeast Sulawesi, Indonesia, yields natural asphalt known as Asbuton, a naturally occurring hydrocarbon substance. Asbuton typically contains bitumen content ranging from 10 to 40%, with the remainder being mineral components. The Asbuton deposit is estimated to comprise approximately 600 million tons [10], equivalent to about 24 million petroleum asphaltenes [13–15]. Ongoing developments in Buton asphalt technology involve the creation of Modified Buton Asphalt (MBA). MBA is produced by blending natural Buton asphalt with petroleum bitumen and subjecting it to processing using machinery that meets specific parameters. MBA, essentially granulated asphalt with reduced mineral content achieved through chemical semi-extraction, can be melted in the asphalt mixing plant tank with or without additional petroleum bitumen before being injected into the aggregate-containing pugmill.

It is envisaged that by adding plastic waste to the asphalt mixture, which will improve its mechanical performance and serve as one of the solutions to the plastic waste problem, originality will be obtained based on the numerous prior studies that have been mentioned above. It is envisaged that a binding substance (modified Asbuton) can be coupled with plastic waste (PET and PP), which is a polymer material. the addition of polymer components, such as PET and PP, to asphalt mixtures that use Asbuton as a binder. Numerous laboratory techniques can be used to carry out modifications, including testing for dominating compounds using the XRD method and testing for compressive strength, which is a mechanical property of asphalt mixtures.

Based on previous research and the background information provided, incorporating plastic waste into asphalt mixtures is believed to enhance the mechanical performance of the asphalt mixture, offering a potential solution to the plastic waste issue. Polymer-based plastic waste, such as PET and PP, can be combined with a binder like Modified Buton Asphalt (MBA). Given this context, the author suggests further investigation into the functionality of asphalt concrete wearing course (AC-WC) mixes. Conducting compressive strength tests using PET and PP plastic waste as additional materials could serve to demonstrate the potential benefits of this approach.

2. Previous Empirical Research Studies

When a road pavement surface layer maintains its shape without permanent deformation over its service life, it functions effectively as a wear layer. However, increasing traffic density is a key factor contributing to road damage and reduced longevity. According to Tayfur et al. (2007) [16] and Birgisson et al. (2008) [17], repeated traffic loads resulting from high traffic density led to the accumulation of permanent deformation in the asphalt concrete mixture, thereby diminishing road performance over time. One approach to addressing this issue is the addition of chemicals to the mixture.

At the municipal level, there has been no dedicated program for managing plastic waste. However, scavengers play a crucial role in the informal recycling of plastic waste. Additionally, there is a growing call for scientists to explore alternatives to traditional plastics or to utilize plastic waste in construction, particularly in road construction. Studies investigating the use of plastic waste in asphalt mixtures have been conducted both domestically and overseas.

Sojobi et al. (2016) [18] conducted a study on the impacts of recycled plastic bottles (PET) used in asphalt concrete for flexible pavement. The findings revealed that adding plastic content of 0%, 5%, 10%, and 20% to the ideal asphalt content could achieve up to 16.7% of the ideal plastic content. The study suggests that utilizing PET plastic bottle waste in asphalt concrete mixtures offers economic and environmental benefits, as evidenced by significant improvements in Marshall properties. Soltani et al. (2015) [19] employed response surface methodology (RSM) to examine the effects of applied stress and temperature on the fatigue life of an asphalt mixture treated with polyethylene terephthalate (PET). The study findings indicate that the selected parameters influence fatigue behavior, with temperature variations having a greater impact on fatigue life (0–1% of aggregate weight) compared to variations in stress and plastic content.

Moghaddam et al. (2013) [20] provided a description of the characteristics of stone-mastic asphalt (SMA) mixtures incorporating PET waste. They found that the addition of 0.18% PET resulted in an asphalt content of 5.88%, which was deemed ideal. Kumar et al. (2022) [21] summarized research findings on the addition of PET plastic waste to asphalt concrete mixtures based on the evaluation of primary data with various mixing processes. They highlighted that utilizing plastic waste in road construction can address environmental concerns while extending the lifespan of roadways. A useful strategy involves thoroughly mixing the plastic into the asphalt-concrete mixture until it coats the aggregate. Dry mixing processes can reduce asphalt usage by 10%. Alternatively, plastic is ground into powder and blended with the asphalt in wet mixing techniques. Using a plastic grid is recommended, as it enhances the durability of the asphalt mixture. Additionally, the addition of plastic to asphalt bitumen helps the asphalt concrete mixture remain stable at high temperatures.

Pasra et al. (2015) [22] introduced a method called flexible pavement for road construction. Their study revealed that adding plastic waste to the mixture enhances the binding qualities, stability, density, and water resistance of the asphalt. However, stability decreases when the plastic concentration exceeds 4%. Plastic incorporation also increases resistance to cracking and heavy traffic on the road. Ahmadinia et al. (2012) [23] investigated Stone Mastic Asphalt (SMA) mixtures with PET plastic bottles as an additional component. The study found that an optimal plastic content of 4 to 6 percent by weight significantly improves the properties of SMA, including stiffness and resistance to permanent deformation (grooving). Baghaee Moghaddam et al. (2012) [24] studied the effects of adding PET waste on the stiffness and fatigue parameters of SMA blends. Their findings demonstrated that even small amounts of plastic bottle waste added to asphalt concrete can enhance the stiffness modulus and fatigue life of the mixture. Ahmadinia et al. (2011) [25] investigated the impact of integrating PET plastic bottle waste into Stone Mastic Asphalt (SMA) mixes. Their findings indicate significant improvements in SMA features with the addition of PET waste. The stiffness of the mixture increases with the addition of PET, as evidenced by the rise in MQ value, while the density of the mixture increases with the addition of VIM. The ideal PET waste percentage in asphalt was found to be 6%. Additionally, the study's findings demonstrate that the addition of plastic waste to asphalt mixtures strengthens them and enhances their durability [26].

Given the significant influence of temperature on the quality of hot asphalt mixtures, it is essential to carefully monitor and maintain the entire process to ensure the desired level of road pavement construction is achieved. With increasing temperature, the elastic modulus value of the layer tends to decrease due to the visco-elastic properties of asphalt, which in turn affect the characteristics of the asphalt layer [27–30].

Utilizing plastic waste in asphalt mixtures has been shown in numerous previous studies to enhance the performance of the mixture, particularly by improving stability, indirect tensile strength, and compressive strength. Additionally, it can reduce cracking caused by heavy loads and provide a solution to the plastic waste issue. One test that is crucial to do to ascertain the asphalt mixture's ability to withstand vehicle loads, particularly compressive loads, in a laboratory setting is its compressive strength.

3. Material and Method

A literature review was conducted as part of the research preparation process to gather insights from previous studies on the utilization of plastic waste as an additive. This study employs experimental methods conducted in a laboratory setting. The initial phase involves setting up the necessary tools and materials, followed by an investigation into the properties of materials in the forms of aggregate, plastic waste, and Modified Buton Asphalt (MBA). In this experimental research, the coarse and fine aggregate, as well as stone ash, were sourced from the Bili-Bili rivers in the Parangloe subdistrict of the Gowa Regency in South Sulawesi Province. MBA with a penetration grade of 60/70 was obtained from one of the MBA producers in Indonesia. Shredded plastic waste is generated by manually grating PET and PP until the material passes through sieve number #4 and is collected in sieve number #50. A research flow chart depicting the methodological procedure is shown in Figure 3. This study consists of a number of lab tests designed to validate the compressive strength of AC-WC asphalt mixtures made with MBA, PET, and PP plastic waste.

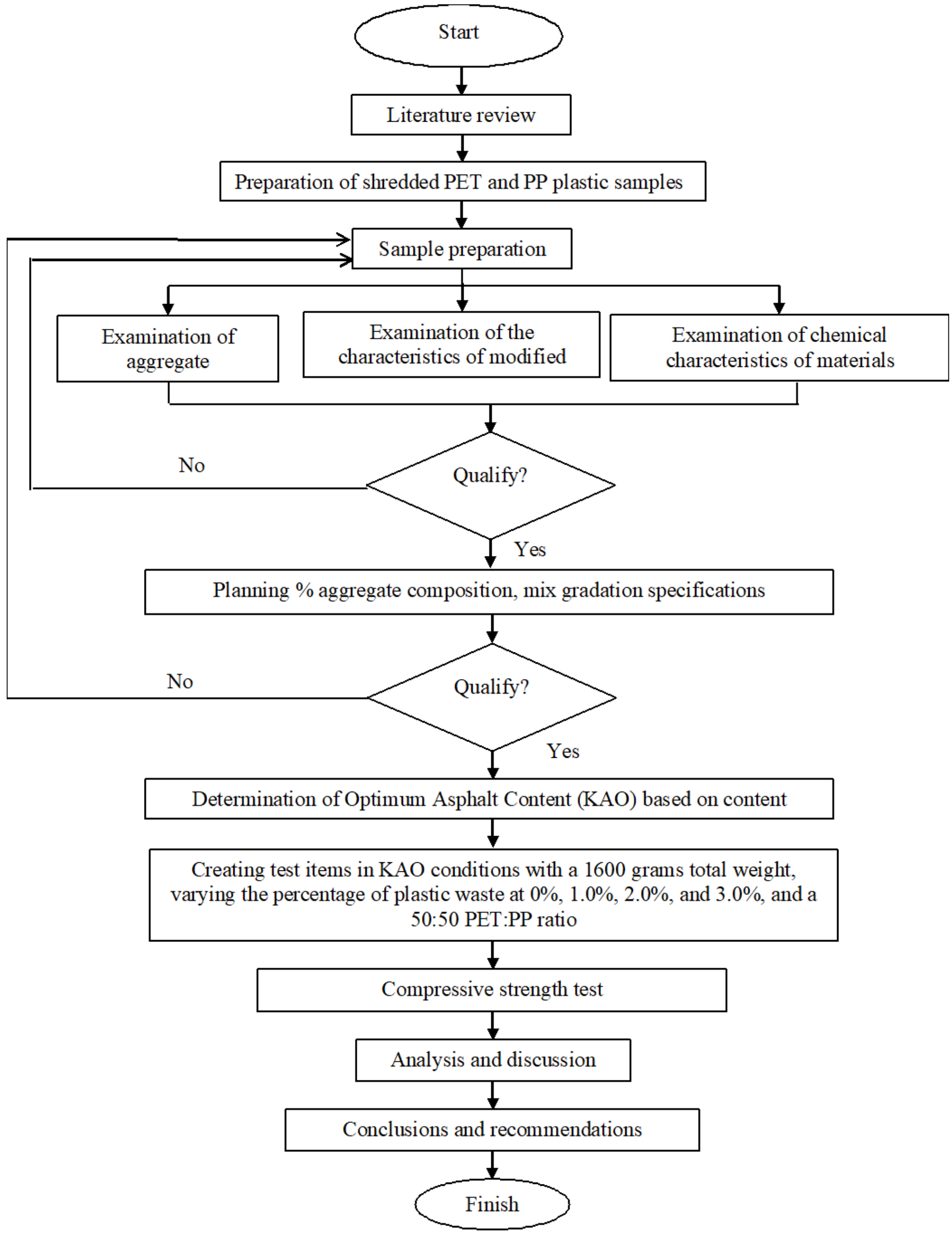


Figure 3. Research flow chart

3.1. Aggregate

The physical properties of the coarse aggregate and fine aggregate (stone ash and stone ash filler) utilized in this research were examined. An analysis of aggregate properties was conducted to evaluate the suitability of the aggregates used. The procedures used to test the properties of coarse aggregate, stone ash, and filler manufactured from stone ash are outlined in Tables 1 to 3. Additionally, the findings of the XRF tests conducted to determine the material's chemical composition are presented in Table 4, which displays the chemical composition of the rock ash filler.

The coarse aggregate used exhibits an aggregate wear of below 40%, indicating high hardness. Additionally, the water absorption level of the coarse aggregate falls below the maximum threshold of 3.0%. These properties align with the requirements of the Indonesian National Standard (SNI) for road materials, as evidenced by the test results for the coarse aggregate (crushed stone), stone ash, and stone ash filler.

The filler in the asphalt mixture functions as a mineral filler, and fillers made from stone ash possess a distinct chemical composition. The primary components include SiO_2, Al_2O_3, Fe_2O_3, CaO, K_2O, and TiO_2, accounting for 49.365%, 34.195%, 5.859%, 5.965%, 2.997%, and 0.777% of the fillers, respectively. Additionally, minor elements such as P_2O_5, BaO, SO_3, MnO, Cr_2O_3, ZnO, and CuO are present. It is anticipated that these material components will contribute to enhancing the compressive strength and other mechanical properties of asphalt mixtures incorporating PET and PP plastic waste.

Table 1. Method and physical characteristics of coarse aggregate

No.	Type of examination	Method of examination	Result of examination	Specification		Unit
				Min.	Max.	
1	Water absorption	SNI 03-1969-2008				
	Crushed stone 0.5 – 1.0 cm		2.069	-	3.0	%
	Crushed stone 1.0 – 2.0 cm		2.078	-	3.0	%
2	Specific gravity	SNI 03-1969-2008				
	Crushed stone 0.5 – 1.0 cm					
	Bulk		2.619	2.5	-	-
	Saturated surface dry		2.668	2.5	-	-
	Apparent		2.769	2.5	-	-
	Crushed stone 1.0 – 2.0 cm					
	Bulk		2.618	2.5	-	-
	Saturated surface dry		2.679	2.5	-	-
	Apparent		2.771	2.5	-	-
3	Flatness index	SNI 03-4137-1996				
	Crushed stone 0.5 – 1.0 cm		20.009	-	25	%
	Crushed stone 1.0 – 2.0 cm		9.378	-	25	%
4	Abrasion	SNI 2417-2008				
	Crushed stone 0.5 – 1.0 cm		25.717	-	40	%
	Crushed stone 1.0 – 2.0 cm		24.357	-	40	%

Table 2. Method and physical characteristics of fine aggregate (stone ash)

No.	Type of examination	Method of examination	Result of examination	Specification		Unit
				Min.	Max.	
1	Water absorption	SNI 03-1970-2008	2.789	-	3.0	%
2	Bulk specific gravity	SNI 03-1970-2008	2.447	2.5	-	-
	Saturated surface dry specific gravity		2.516	2.5	-	-
	Apparent specific gravity		2.626	2.5	-	-
3	Sand Equivalent	SNI 03-4428-1997	89.658	50	-	%

Table 3. Method and physical characteristics of filler (stone ash)

No.	Type of examination	Method of examination	Result of examination	Specification		Unit
				Min.	Max.	
1	Water absorption	SNI 03-1970-2008	2.278	-	3.0	%
2	Bulk specific gravity	SNI 03-1970-2008	2.598	2.5	-	-
	Saturated surface dry specific gravity		2.647	2.5	-	-
	Apparent specific gravity		2.759	2.5	-	-
3	Sand Equivalent	SNI 03-4428-1997	69.569	50	-	%

Table 4. Chemical characteristics of filler stone ash (XRF test)

Compound	Content (%)
SiO_2	49.357
Al_2O_3	34.200
Fe_2O_3	5.789
CaO	5.856
TiO_2	0.767
K_2O	2.987
P_2O_5	0.265
BaO	0.219
SO_3	0.179
MnO	0.108
Cr_2O_3	0.0190

3.2. Modified Buton Asphalt (MBA)

The binder used in this study is modified asphalt. To evaluate the physical characteristics of the asphalt, which are linked to its performance, an analysis of its properties was conducted. The results of the modified Buton Asphalt (MBA) tests are presented in Table 5. The analysis of the properties of modified asphalt, as shown in Table 5, indicates that the asphalt used in this study meets the requirements of the Indonesian National Standard (SNI). The chemical properties of modified Buton asphalt (MBA) are presented in Table 6.

Table 5. Method and physical characteristics of Modified Buton Asphalt (MBA)

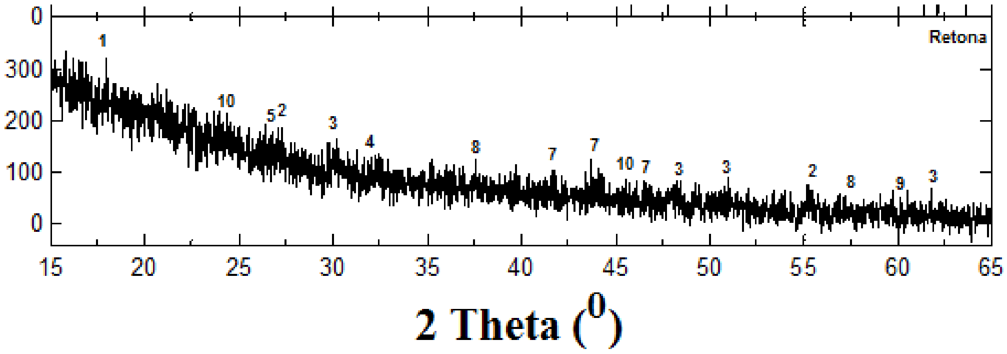
No.	Type of examination	Method of examination	Result of examination	Specification		Unit
				Min.	Max.	
1	Penetration prior to weight loss	SNI 06-2456-1991	78.589	60	79	mm
2	Soft point	SNI 06-2434-1991	41.999	48	58	ºC
3	Ductility at 25°C, 5 cm/min	SNI 06-2432-1991	113.998	100	-	cm
4	Flash point	SNI 06-2433-1991	279.979	200	-	ºC
5	Specific gravity	SNI 06-2441-1991	1.119	1	-	-
6	Weight loss	SNI 06-2440-1991	0.298	-	0.8	%
7	Penetration after losing weight	SNI 06-2456-1991	85.878	54	-	mm

Table 6. Chemical characteristics of Modified Buton Asphalt (MBA)

Compound	Content (%)
SO_3	69.137
CaO	22.174
SiO_2	4.281
Cl	1.778
Fe_2O_3	1.196
V_2O_5	1.049
K_2O	0.258
NiO	0.097
Cr_2O_3	0.030
SO_3	69.137
CaO	22.174

According to the Shell Bitumen Handbook (2015) [5], asphalt is composed of hydrocarbon compounds, nitrogen compounds, and various other chemical compounds. The test results indicate that modified asphalt has a high concentration of SO_3, a constituent element of asphalt, at 69.137%, followed by CaO at 22.174%, and SiO_2 at 4.281%. Other components include Cl, Fe_2O_3, V_2O_5, K_2O, NiO, and Cr_2O_3, with relative percentages of 1.778%, 1.196%, 1.049%, 0.258%, 0.097%, and 0.030%, respectively. Figure 4 illustrates the relationship between the 2ϴ angle and the intensity of modified Buton asphalt. The test sample and the X-rays interact to form diffraction patterns, which are recorded and produced by X-ray diffraction. Information regarding the amorphous and crystalline states of polymers, as well as their structure, can be obtained using X-ray diffraction.

The XRD test results of modified Buton asphalt (MBA) type Retona Blend 55 indicate that the amount of bitumen or total of the materials represented by numbers 1 ($C_{20}N_2O_2S$), 2 ($C_4H_7NO_3$), and 7 (C) is 31%, 12.2%, and 26%, respectively, with a combined percentage of 82.3%. Meanwhile, the minerals contained, represented by numbers 4 (BaO_3Ti), 5 (SiO_2), 6 (Fe_2O_3), 8 (CaO_4S), 9 (CaO), and 10 (SO_3), are 1%, 3.6%, 3.1%, 7%, 2.1%, and 0.9%, respectively, with a total percentage of 17.7%. This demonstrates that Retona Blend 55, a semi-extracted Asbuton, typically contains 70% bitumen and 30% minerals.



No.	Name	Compound formula	Content (%)
1		$C_{20}N_2O_2S$	31
2		$C_4H_7NO_3$	12.2
3	Wollastonite-2M	CaO_3Si	13.1
4	Barium titanate	BaO_3Ti	1
5	Quartz	SiO_2	3.6
6	Iron (III) oxide - $-alpha Hematite	Fe_2O_3	3.1
7	Carbon	C	26
8	Calcium Sulphate Anhydrite	CaO_4S	7
9	Lime	CaO	2.1
10		SO_3	0.9

Figure 4. Relationship between phase angle and intensity of modified Buton asphalt

3.3. Plastic Waste

In addition to the challenge of deteriorating road infrastructure, the issue of plastic waste poses another significant concern. Addressing these two challenges effectively requires relevant academic research. One potential solution involves incorporating plastic debris as a supplementary ingredient in asphalt mixtures, especially in AC-WC mixtures. Utilizing additives in asphalt-concrete mixtures can enhance the overall performance, particularly in terms of asphalt mixture performance and the durability of asphalt concrete under repeated road loading. In this study, plastic waste, a lesser-quality polymer, is employed as an additional component.

Angelone et al. (2016) [11] outlines two methods for incorporating plastic into asphalt mixtures:

a. Wet method. In this approach, plastic is added to hot asphalt and vigorously mixed until a uniform mixture is achieved. The cost of producing modified asphalt using this method is significantly higher compared to regular asphalt, as it requires additional expenses such as fuel and a high-speed mixer.

b. Dry method. In this method, hot asphalt is introduced after placing plastic into the heated aggregate, which has been heated to the mixture's temperature. This process may be simpler than the wet method since it only involves adding plastic to the hot aggregate without the need for a mixer. However, care must be taken to ensure that the levels of plastic added or blended are uniform and homogeneous.

In this study, plastic was incorporated into the asphalt-concrete mixture using a dry approach. According to an economic analysis, the dry method is more cost-effective than the wet method because it mixes more quickly, requires no additional equipment for mixing, and is easier to handle [11]. Additionally, it can enhance the binding properties of the aggregate in the mixture, slow down road deterioration, and reduce the amount of asphalt required in the mix [31, 32].

Angelone et al. (2016) [11] suggest that the amount of plastic added to the mixture should not exceed 17%, as doing so may lead to undesirable outcomes. Furthermore, Moghaddam et al. (2012) [24] argue that adding a small amount of plastic (0.2-1% of the aggregate weight) can increase the mixture's density and stiffness. According to A. Maal et al. (2017) [26], asphalt concrete can withstand more loading cycles with denser mixtures, thereby extending the mixture's fatigue life. The distinctions between PP and PET plastic types are detailed in Table 7.

Table 7. Differences between the plastic types PET and PP

No.	Differences	PP Plastic	PET Plastic
1	Compound formula	$(C_3H_6)_x$	$C_{10}H_8O_4$
2	Characteristic	It feels lighter in quality, soft and waxy, and transparent to some extent.	High heat resistance, excellent sanitary qualities, and high chemical stability
3	Basic material	Polymer	Polyester
4	Melting point	160^0C	260^0C
5	Density	0.855 g/cm^3	1.4 g/cm^3

3.4. Unconfined Compressive Strength (UCS) Test

Testing for compressive strength involves identifying failures or cracks that occur after subjecting the test object to its maximum stress level. Additionally, changes in the length of the test item can be detected by reading the deflection value from the installed and connected Linear Variable Displacement Transducers (LVDT) to the data logger.

The ASTM D1074-09 standard, adopted by SNI 03-6758-2002, outlines the compressive strength testing procedure. LVDT sensors operate based on a differential transformer with variable coupling between the primary and secondary coils. LVDTs can function as mechanical distance sensors, angle sensors, and more. They consist of a primary coil, two secondary coils, and a ferromagnetic material core. The iron core is placed in a non-magnetic sleeve cavity after winding the coils around it. The two secondary coils, wound on either side of the primary coil in the middle of the sleeve, have the same number of turns and are connected in series in opposite directions.

To capture deflection readings, a data logger is connected to a universal testing machine and an LVDT, as depicted in Figure 5, which schematically represents the compressive strength testing procedure on asphalt mixes.

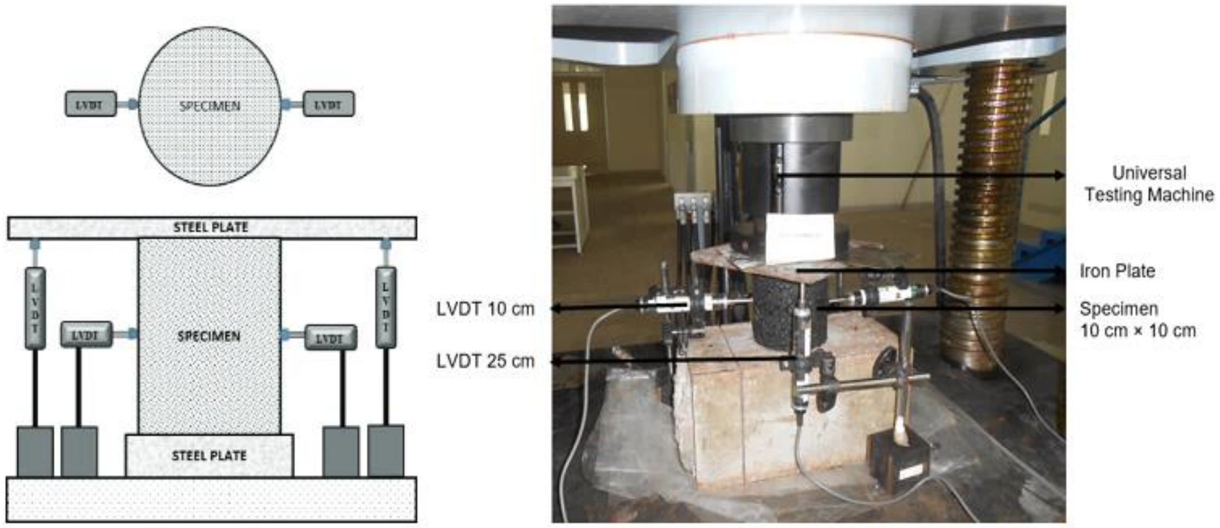
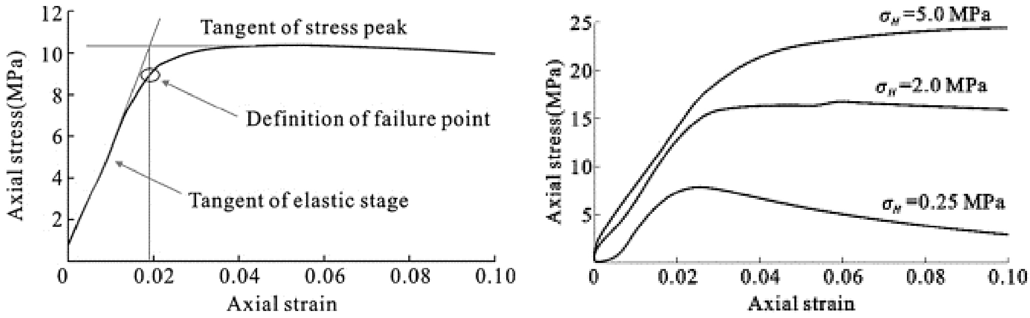


Figure 5. Unconfined compressive strength test

3.5. Stress-Strain Relationship

Researchers utilized existing models for low- to normal-strength concrete to develop stress-strain curve models for permeable concrete and compared experimental outcomes. This study will adopt a similar comparison approach, drawing on insights from Sazid & Ahmed (2019) [33] to explore the correlation between the stress-strain behavior of asphalt concrete (AC) and that of cement concrete. Previous research by Sazid & Ahmed (2019) [33], Alsayed et al. (2020) [34], and Carriera & Chu (1985) [35] concluded that the ascending and descending branches of the concrete stress-strain curve are significantly influenced by the strain corresponding to the peak stress, demonstrating a linear relationship. This connection between compressive strength and associated strain under uniaxial compression will be examined for AC using the uniaxial compression test method.

Zheng & Huang (2015) [36] introduced a novel triaxial technique to explore the failure criteria of asphalt mixtures. Shear failure typically manifests as an increase in confining pressure, leading to reduced compressive strength, while rheological failure results from further elevation of confining pressure. Triaxial tests allow for the examination of more failure modes compared to uniaxial tests. In their study, Zheng & Huang [36] subjected specimens to strain and stress tests. The curves of specimens with higher horizontal stress values initially displayed rising limbs that plateaued after failure or surpassing the elastic state. Conversely, as depicted in Figure 6-b, specimens with lower horizontal stress exhibited initially increasing curves that peaked before descending. This results in a steeper or more pronounced descending part of the stress-strain curve as the applied horizontal stress approaches zero.



(a) (b)

Figure 6. Link between stress and strain with high horizontal stress (b). Very low horizontal stress in the stress-strain relationship [36]

Starodubsky et al. (1994) [37] investigated the stress-strain relationship of asphalt concrete under compression through both uniaxial and triaxial compression experiments. They observed similar failure modes to those reported by Zheng & Huang (2015) [31], characterized by an initial linear climb, followed by a peak and a subsequent nonlinear descent with a moderate slope. Additionally, their research revealed that specimens subjected to triaxial compression tests exhibited higher yield points or maximum stress compared to those tested uniaxially. The study demonstrated that specimens with varying characteristics, such as aggregate type, compaction effort, asphalt content, height, and loading mode, exhibited stress-strain relationships akin to concrete. Failure typically occurred through splitting or shear failure, evidenced by linear branches in the stress-strain curve transitioning smoothly into nonlinear regions with microcracks, consistent with Hooke's law.

Wang et al. (2015) [38]. studied the behavior of asphalt concrete mixtures under triaxial pressure. They conducted triaxial compression monotonic tests on both porous and dense asphalt concrete. Their findings indicated that compressive failure strength and stiffness of asphalt concrete increased with decreasing temperature, increasing loading rate, and increasing confinement.

4. Results and Discussion

4.1. Combination of PET and PP Plastic Waste

The study conducted by Irianto et al. (2023) [39] utilized a pyrolysis method to blend PET and PP plastic waste. Pyrolysis was conducted in the laboratory using a retch approach with a 1:1 ratio of the two plastics, subjected to agitation (5 min + 5 Hz). It was observed that polypropylene melts at 160°C, while polyethylene terephthalate plastic melts at 260°C, as per the measurements conducted. Although the diffraction patterns of the heated and unheated polymers were identical, their intensities varied significantly. Effective fusion of the pyrolyzed plastic wastes was achieved by heating them at 100°C for 30 minutes. Figure 7 illustrates the physical appearance of PET and PP plastic waste.

Figure 7. Physical appearance of PET and PP plastic waste

XRD analysis provided distinct spectral lines for each polymer, with the intensity of these lines influenced by the composition of the plastic mix. The pyrolyzed plastic waste showed promise as a substitute for aggregates in asphalt mixtures. The research concludes that pyrolysis is a viable method for blending and repurposing thermoplastic polymers. Through XRD analysis, structural and chemical characteristics of mixed plastics can be examined, providing valuable insights into the relationship between electromagnetic wave absorption performance and composition. The potential use of pyrolyzed plastic waste in asphalt mixes highlights how this technique could support the circular economy and mitigate the environmental impact of plastic waste.

4.2. Asphalt Mix Gradation

The anticipated combined percentage of the intended aggregate composition was determined by multiplying the comparison value of the intended aggregate composition by the percentage value that passed the sieves for stone (1-2 cm), crushed stone (0.5-1 cm), and stone ash. Figure 6 illustrates the combined aggregate grade. Comparing the aggregate composition percentages for stone ash, coarse crushed stone aggregate (0.5–1 cm), and coarse crushed stone aggregate (1-2 cm), they are 19%, 36%, and 45%, respectively. The obtained percentage of mixed aggregate is calibrated to align with the specified interval value of the Indonesian National Standard. The combined aggregate design lies between the higher and lower thresholds in the Indonesian National Standard specification interval for road materials to achieve the optimal mixture.

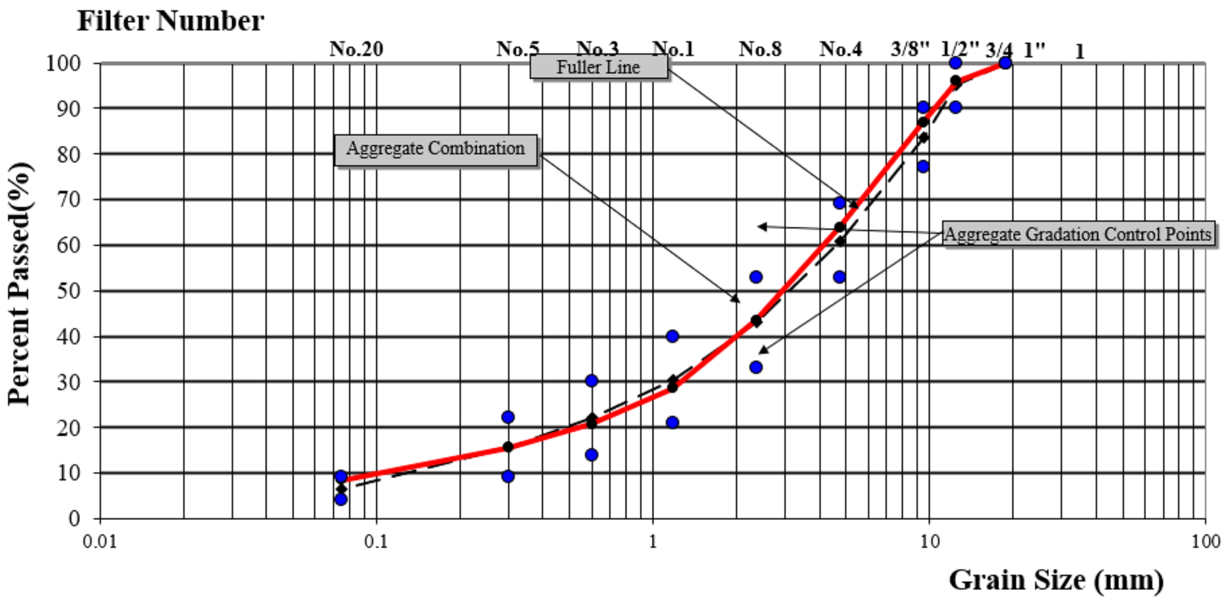


Figure 8. Aggregate gradation of AC-WC mixture

4.3. Mixtures Design of Asphalt Mix Transformation PET and PP Plastic Waste

The approximation equation for determining asphalt content revealed that the modified Buton asphalt (MBA) content of the test object was 6.0%. Computation based on the Indonesian National Standard led to this determination. Consequently, asphalt content variations of 5.0%, 5.5%, 6.0%, 6.5%, 7.0%, and 7.5% were considered for the porous asphalt mixture in this study. Through volumetric analysis including VIM, VMA, and VFB, as well as stability characteristics such as flow, Marshall quotient, and stability, the optimal asphalt amount required in hot asphalt mixtures with MBA was determined to be 6.25%. Reference to SNI 06-2489-1991 guided the analysis to ascertain the ideal asphalt quantity in a hot asphalt mixture utilizing river stone aggregate.

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Table 8. Material composition in weight for 1600 grams of test object

No	Description			Unit	Plastic waste content (%)			
					0.0	1.0	2.0	3.0
A	**Plastic waste weight (PET + PP)**			**gr**	**0.00**	**15.00**	**30.00**	**45.00**
B	**MBA weight (6.25%)**			**gr**	**75.00**			
C	**Gradation of combined aggregates**				**Aggregate weight according to sieve size**			
	Filter	**% Passed**	**% Retained**					
1	3/4"	100.00	0.00	gr	-	-	-	-
2	1/2"	96.00	4.00	gr	60.04	58.54	57.04	55.54
3	3/8"	86.93	9.07	gr	136.05	134.55	133.05	131.55
4	No. 4	63.90	23.03	gr	345.38	343.88	342.38	340.88
5	No. 8	43.56	20.34	gr	305.06	303.56	302.06	300.56
6	No. 16	28.62	14.94	gr	224.13	222.63	221.13	219.63
7	No. 30	20.76	7.87	gr	118.00	116.50	115.00	113.50
8	No. 50	15.60	5.16	gr	77.40	75.90	74.40	72.90
9	No. 100	10.79	4.80	gr	72.02	70.52	69.02	67.52
10	No. 200	8.43	2.37	gr	35.53	34.03	32.53	31.03
11	PAN	6.06	0.00	gr	126.39	124.89	123.39	121.89
12	PET (50%)	-	-	gr	-	7.50	15.00	22.50
13	PP (50%)	-	-	gr	-	7.50	15.00	22.50
	Total		100.00	gr	1,525	1,525	1,525	1,525
D	Weight of specimen (A + B + C)			gr	1,600	1,600	1,600	1,600

4.4. Stress-Strain Behavior

This study examines the stress-strain relationship resulting from compressive loading of the AC-WC mixture, considering different levels of plastic waste: 0%, 1%, 2%, and 3%, with a 50:50 ratio between PET and PP plastic waste. Figure 9 displays the stress-strain relationship of the AC-WC mixture without plastic waste. The linear relationship between stress and strain represents the elastic region, observed up to 60% of the peak compressive strength value. Peak stress ranged from 1.224 to 1.288 MPa, with peak horizontal strain of 0.0035 to 0.0040 mm/mm and peak vertical strain of 0.020 to 0.030 mm/mm. The graph illustrates a near-perfect match between stress and strain values for specimens 1, 2, and 3.

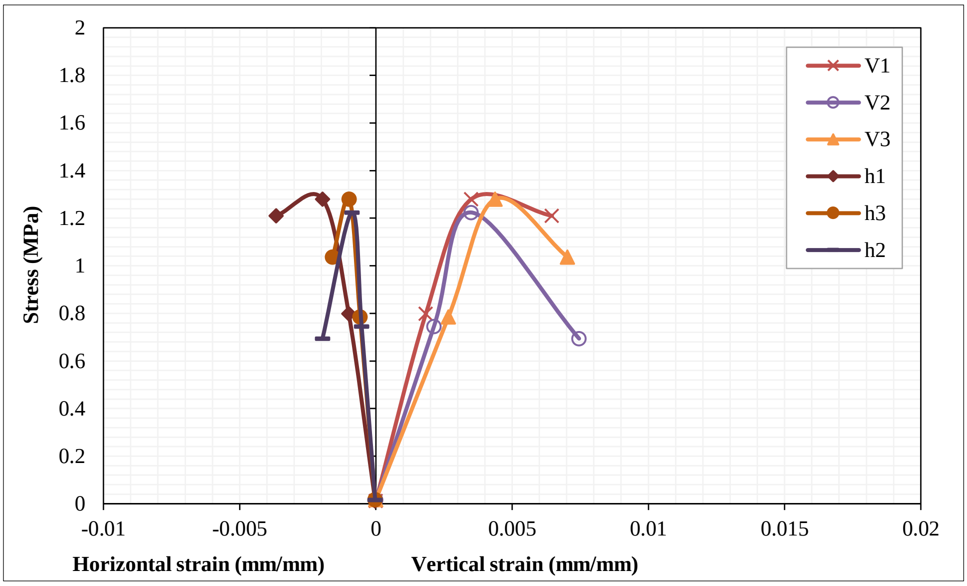

Figure 9. Stress-strain behavior of test specimens without plastic waste

Figure 10 depicts the stress-strain relationship of the AC-WC mix with 1% plastic waste and a 50:50 blend of PET and PP plastic. The elastic region is represented by the linear relationship between stress and strain, observed up to 70%

of the peak compressive strength value. Peak stress ranged from 2.237 to 2.538 MPa, with peak horizontal strain of 0.0060 to 0.0120 mm/mm and peak vertical strain of 0.032 to 0.037 mm/mm. The graph shows a close alignment between stress and strain values for all three test specimens, indicating similar compressive strengths.

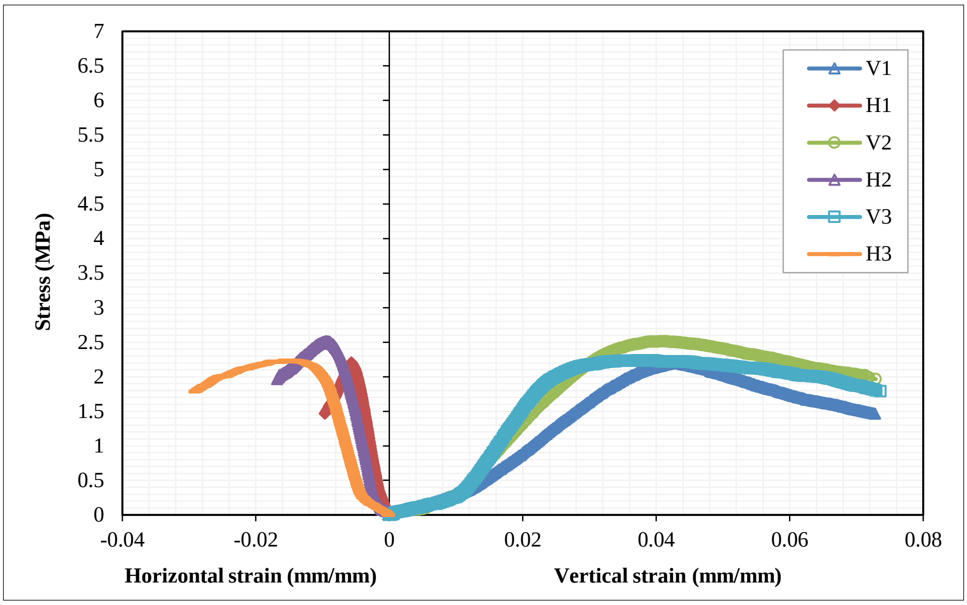

Figure 10. Stress-strain behavior of test specimens with 1% plastic waste

Figure 11 illustrates the stress-strain relationship of the AC-WC mixture with 2% plastic waste and a 50:50 blend of PET and PP plastic. The linear relationship between stress and strain represents the elastic region, observed up to 63% of the peak compressive strength value. Peak stress ranged from 3.928 to 4.246 MPa, with peak horizontal strain of 0.010 to 0.015 mm/mm and peak vertical strain of 0.036 to 0.042 mm/mm. The graph indicates a close alignment between stress and strain values for all three test specimens, suggesting similar compressive strengths.

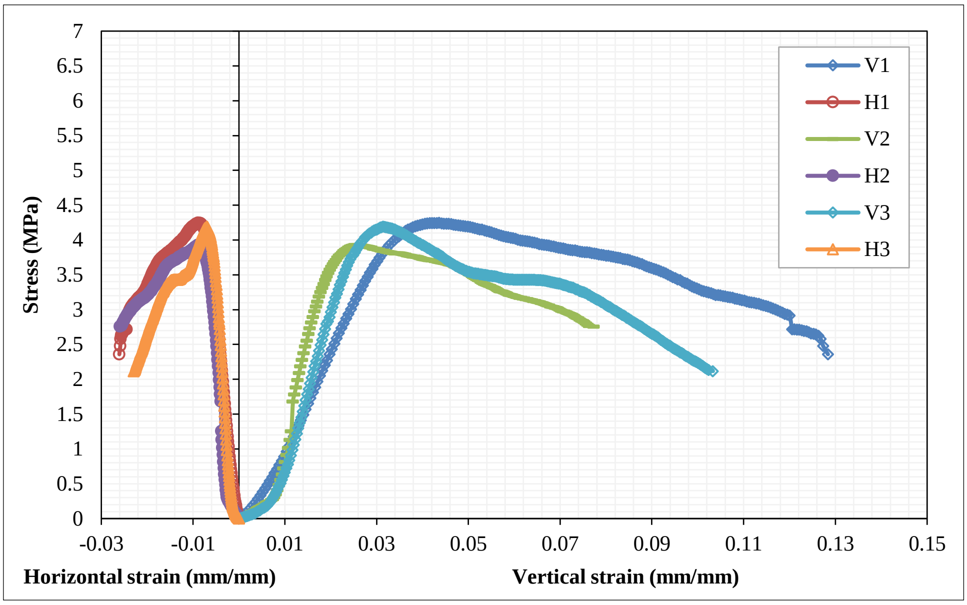

Figure 11. Stress-strain behavior of test specimens with 2% plastic waste

Similarly, Figure 12 depicts the stress-strain relationship of the AC-WC mix with 3% plastic waste and a 50:50 blend of PET and PP plastic. The linear relationship between stress and strain is observed up to 63% of the peak compressive strength value, representing the elastic region. Peak stress ranged from 4.369 to 6.151 MPa, with peak horizontal strain of 0.005 to 0.013 mm/mm and peak vertical strain of 0.016 to 0.020 mm/mm. The graph demonstrates a close correspondence between stress and strain values for all three test specimens, indicating comparable compressive strengths.

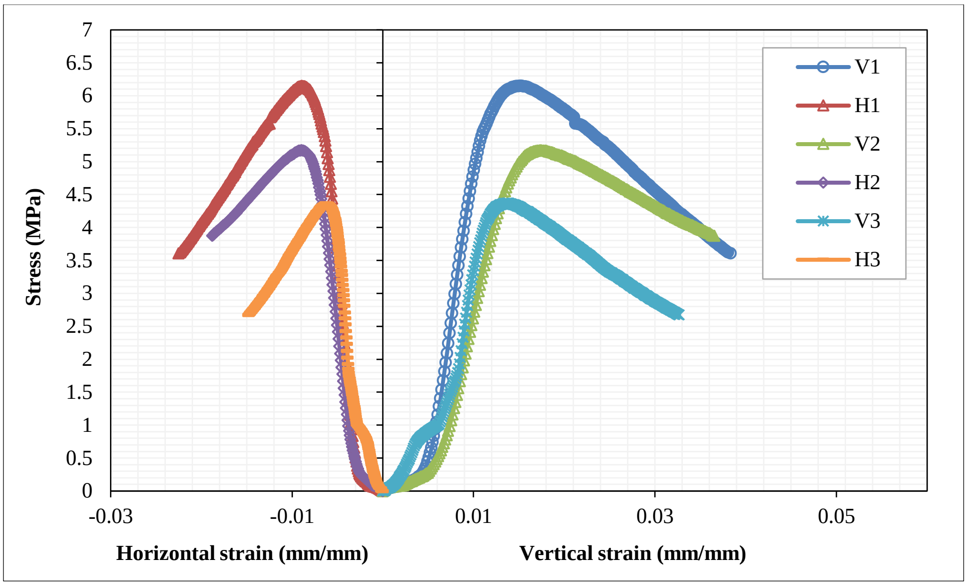

Figure 12. Stress-strain behavior of test specimens with 3% plastic waste

4.5. Compressive Strength

Table 9 displays the compressive strength values for the AC-WC mixture, which is supplemented by PET and PP plastic waste. It is evident that the AC-WC mixture, which did not include plastic waste as an addition, achieved an average compressive strength value of 1.26 MPa from three test objects. In the AC-WC mixture, it is 2.31 MPa with 1% plastic waste in a 50:50 PET:PP ratio. It is 4.11 MPa in the AC-WC mixture, which uses 2% plastic waste in a 50:50 PET:PP ratio. It is 5.23 MPa in the AC-WC mixture, which uses 3% plastic waste in a 50:50 PET:PP ratio. Better component binding is the reason behind the rise in compressive strength values that polymers provide to hot-mix asphalt. Waste plastic from PET and PP is used in this study. Additionally, it is evident that the compressive strength value increases with increasing plastic content. Since the aggregate is heavily covered, there is little flow, and changes are difficult to make, the modified Asbuton mixture's high compressive strength and Marshall Quotient value are correlated. This will ultimately increase the binding force between the aggregates in the mixture when it is loaded. A smaller flow value results from a mixture's increased stability value, which is caused by stronger aggregate bonds.

Table 9. Compressive strength of the AC-WC mixture which uses PET and PP plastic waste

No.	Plastic presentation		Plastic content (%)	Compressive strength (MPa)	
	PET	PP			
				1.28	
1	0%	0%	0	1.22	1.26
				1.28	
				2.20	
2	50%	50%	1	2.51	2.31
				2.23	
				4.24	
3	50%	50%	2	3.92	4.11
				4.19	
				6.15	
4	50%	50%	3	5.17	5.23
				4.37	

The findings from the compressive strength test clearly indicate a positive correlation between the amount of plastic waste and the compressive strength value of the asphalt mixture. This increase in compressive strength can be attributed to several factors, including the enhanced stiffness and density of the mixture as indicated by the high Marshall Quotient (MQ) value. A high MQ value typically signifies increased stiffness and brittleness in the asphalt mixture, which contributes to higher compressive strength. Furthermore, the addition of polymeric waste plastic to Asbuton, a porous material with low bitumen penetration, results in improved bonding and interlocking capacity between the aggregate, plastic waste, and modified Asbuton. This enhancement in aggregate characteristics, coupled with improved bonding, ultimately leads to an increase in compressive strength.

Experts quoted in the "Full Scale Application of Plastic Waste Asphalt Technology" emphasize the positive effects of adding plastic waste to hot aggregate, including improved water absorption capacity and reduced friction. These improvements further contribute to the overall enhancement of the asphalt mixture's properties and, consequently, its compressive strength.

The utilization of PET plastic waste in this study is primarily justified by its unique properties, particularly its semi-crystalline nature and transition temperature (Tg) of approximately 70°C. As indicated in Table 9, when incorporated into the asphalt mixture, PET undergoes changes in its properties, potentially becoming stiffer and more stable. This change is attributed to PET retaining its semi-crystalline structure even after being mixed into the asphalt.

Despite PET's high melting point (approximately 250°C), which exceeds the maximum temperature typically used for admixtures in hot mix asphalt (less than 180°C), its utilization is still feasible. This is because the study demonstrates that PET's properties can still positively influence the asphalt mixture, even without reaching its melting point. Additionally, the study by Casey et al. (2008) [39] suggests that incorporating polymers with high melting points, such as PET, into bitumen may present challenges due to their resistance to mixing. Therefore, while PET's high melting point may pose logistical challenges in the mixing process, its unique properties and potential benefits justify its use as an additive in hot mix asphalt mixtures.

As previously noted, PET was added to the mixture at the end of the dry process in this investigation. The goal was to preserve PET in its native composition, which is a semi-crystalline resin, with as few alterations as possible to its primary features and shape. The highest compressive strength value was found in the 3% plastic waste composition, which consisted of 50% PET and 50% PP. Several factors contribute to the high modulus of elasticity in asphalt mixtures containing plastic waste, including PET, PP, and MBA:

- The extremely low bitumen penetration value of the asphalt mixture, approximately 16 mm, has resulted in increased hardness, which affects the asphalt mixture's elastic modulus.
- The presence of calcium oxide in the asphalt mixture affects stiffness and, consequently, strength.
- The addition of silicon oxide to the asphalt mixture has increased its elastic modulus, making it stiffer and more cohesive.

4.6. Variables' Effects on Mixed Compressive Strength Measures

This study investigated the relationship between the compressive strength value of the AC-WC mixture and several independent factors, including plastic waste content, the percentage ratio of PET and PP, and asphalt content (MBA). To analyse this relationship, a variance level comparison test, specifically the F-test and t-test, was employed.

The purpose of the F-test, also known as the simultaneous test, is to determine how the dependent variable (mixed resilience modulus value) is collectively and simultaneously influenced by all independent factors. According to the SPSS data, the F_{table} value is 7.41, and the F_{count} test result is 106.595, with a probability value of 0.000. This indicates that F_{count} (108.765) > F-table (7.41), and the probability value is 0.00 < 0.05. Consequently, the compressive strength value of the AC-WC mixture, which utilizes a combination of PET and PP plastic waste, is significantly influenced by the plastic waste content, the percentage ratio of PET and PP, and the asphalt content (MBA) all at the same time.

A partial test, such as the t-test, examines the relationship between the dependent variable (the compressive strength value) and each independent variable (the amount of plastic trash, the proportion of PET and PP, and the amount of asphalt (MBA)). According to the SPSS findings presented in Table 10, the t_{count} value of the asphalt content variable is 15.764, while the t_{table} value is 2.305. Thus, we have t_{count} (15.744) > t_{table} (2.305). Furthermore, the probability value obtained is 0.00 < 0.05. Based on these two findings, it can be inferred that the variable representing the plastic waste content significantly affects the value of the compressive strength modulus. Additionally, the negative t sign indicates a unidirectional relationship with the dependent variable (compressive strength value), demonstrating that the mixture's compressive strength value increases with the amount of plastic trash used. However, laboratory testing results revealed that the mixture's compressive strength value could be increased by adding plastic trash up to a specific amount and percentage.

Table 10 further demonstrates that the t_{count} value of 16.316 for the variable representing the percentage comparison between PET and PP is greater than the t_{table} value of 2.305, resulting in t_{count} (16.316) > t_{table} (2.305). Additionally, the probability value obtained is 0.00 < 0.05. Based on these two findings, it can be inferred that the mixture's compressive strength value is significantly influenced by the variable percentage ratio of PET and PP. Furthermore, a positive t-sign is observed, indicating a unidirectional relationship between the independent variable (mixed compressive strength modulus value) and the dependent variable. This is consistent with laboratory test results, which suggest that the compressive strength value of the AC-WC mixture (a blend of PET and PP plastic waste) will be more affected by the percentage ratio of PET and PP used.

Table 10. SPSS t test (partial test) results

Independent variable	t	Sig.
Plastic waste contents	-15.764	0.000
Percentage comparison of PET and PP	16.316	0.000
Asphalt content (MBA)	-2.305	0.079

Furthermore, Table 10 demonstrates that the t_{count} value of the variable asphalt content (MBA) is 2.205, whereas the t_{table} value is 2.305. Consequently, t_{count} (2.205) < t_{table} (2.305). Additionally, the probability value obtained of 0.079 > 0.05. Based on these two findings, it can be inferred that the mixture's compressive strength value is not significantly affected by the variable asphalt content (modified asphalt). Furthermore, a negative t-sign is observed, indicating a unidirectional relationship between the independent variable (mixed compressive strength value) and the dependent variable. This is consistent with the findings of laboratory experiments, which demonstrate that the compressive strength value of the AC-WC mixture—combining waste PET and PP plastic—will decrease with increasing asphalt content (MBA) added to the mixture.

5. Conclusion

In conclusion, the study demonstrates that the inclusion of PET and PP plastic waste in the AC-WC mixture at a 50:50 ratio substantially improves its compressive strength. With plastic contents of 1%, 2%, and 3%, the mixture exhibited compressive strength values of 2.31 MPa, 4.11 MPa, and 5.23 MPa, respectively, indicating a clear positive correlation between plastic waste content and compressive strength. This highlights the potential of using plastic waste as an effective additive in asphalt mixtures, presenting a sustainable solution to both waste management and infrastructure development challenges.

Moreover, the study underscores the versatility of blending materials with diverse physical properties, suggesting opportunities for innovative approaches in construction practices. By integrating waste resources such as PET and PP plastic waste with natural materials like Buton asphalt, the study advocates for environmentally friendly and sustainable infrastructure development practices. This aligns with the broader objective of promoting ecologically sustainable growth. At a plastic content of 3% of the aggregate's weight, PET and PP plastic waste can be added to the AC-WC combination as an extra material. The findings of this study can aid in the development of national infrastructure through the utilization of waste materials, particularly the combined PET and PP plastic waste, and natural resources like Buton asphalt. This is anticipated to enhance the adoption of environmentally sound development practices.

6. Declarations

6.1. Author Contributions

Conceptualization, I.R. and M.T.; methodology, M.T.; software, F.E.P.L.; validation, I.R., M.T., and F.E.P.L.; formal analysis, M.T.; investigation, I.R.; resources, I.R.; data curation, F.E.P.L.; writing—original draft preparation, I.R.; writing—review and editing, M.T.; visualization, M.T.; supervision, I.R.; project administration, F.E.P.L.; funding acquisition, M.T. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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